TEMPERATURE GRADIENTS IN THE CHANNELS OF A SINGLE-SCREW EXTRUDER

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Abstract

A novel fluorescence analytical technique was used to measure the polymer temperature inside an operating extruder. The method allowed the temperature measurement of the polymer without interference from the surrounding metal parts. This paper will show some temperature data for molten polycarbonate in a single-screw extruder under processing conditions.

Introduction

The temperature of a molten polymer stream is a key processing parameter to know for all processes. The process temperature affects many things including the viscosity, density of the resin, and degradation kinetics (1). The temperature of the molten resin, however, is rarely known with great accuracy due to problems associated with thermocouples, the most common instrument for temperature measurement. In commercial processes, thermocouples transfer energy readily to and from the equipment and thus are highly influenced by the temperature of the surrounding metal.

Numerous methods have been developed to minimize the energy transfer associated with thermocouple use (2-5). The most common method is to place small thermocouples in a bridge assembly in a transfer pipe. For this arrangement, thin-wire thermocouples are imbedded into a high-temperature polymeric support bridge, and the wires are aligned in the flow direction for a short distance. These bridges provide an accurate temperature measurement of the flow, but the devices are extremely delicate and cannot be used to measure temperatures inside an extruder. Esseghir and Sernas (6) developed a mechanical system to insert and retract a small thermocouple through a barrel wall of a lab extruder to measure the temperature in a rotating screw channel. Like the thermocouple bridge, this system was very delicate and only for lab use.

Several non-invasive methods exist for temperature measurement including infrared (IR) (7) and fluorescent techniques. Fluorescent dyes offer a unique and non-invasive method of temperature measurement. These dyes act as molecular probes, responding to the molecular environment in which they exist. Their observed spectra indicate the local environmental conditions. Thus, a temperature deduced from a fluorescence spectrum yields a true resin temperature. The fluorescence method used here employs a sensor with confocal optics, permitting temperature measurements at different distances from the sensor tip (8-10); i.e., a temperature profile.

The goal of this work is to apply a novel fluorescence temperature measurement method to single-screw extrusion. Temperature measurements made deep into rotating metering channels as a function of screw speed, screw design, and melt flow rate (MFR) for polycarbonate (PC) resins will be presented.

Materials

Two commercial-grade PC resins were used for this study. The resins were manufactured by The Dow Chemical Company, and they had melt flow rates (MFR) of 6 and 23 g/10 min (ASTM D-1238, Condition O, 300°C, 1.2 kg). These resins were used previously in a melting rate study (11). The resins were dried, compounded using a twin-screw extruder with 1.6×10^{-5} mass fraction of perylene dye, and then they were re-pelletized.

The perylene-PC compounded resin pellets were dried overnight at 122 °C in a dehumidifying desiccant dryer prior to extrusion. Shear viscosities of the resins at 280 ^{o}C are shown by Figure 1.

Extrusion and Temperature Measurement Equipment

A highly-instrumented, 63.5 mm diameter extruder with a 21 length-to-diameter ratio (L/D) was used to collect extrusion process data. This extruder had eleven pressure transducers along the axis of the barrel to measure pressures along the screw. The pressure sensor positioned at 19 diameters from the start of the screw was removed and replaced with a fluorescence optical sensor. The extruder was equipped with three barrel temperature control zones. The barrel temperatures were set at 275 °C for all zones.

A conventional single-flighted, square-pitched screw with a compression ratio of 2.8 was used for most of the studies (12). The screw had a feed depth of 8.9 mm for 6 diameters, a transition length of 8 diameters, and a meter depth of 3.18 mm for 7 diameters. The specific drag flow rate, that is the specific rate expected for just rotation with no imposed pressure gradients, was calculated at 0.94 kg/(h rpm). The optical temperature sensor was positioned over the constant depth metering section. Previous work (11) indicated that these PC resins were completely molten at this barrel position for this screw.

A high-performance Energy Transfer (ET) screw was also used for the study. This screw will be referred to as the mixing screw in the remainder of the paper. This screw was described previously (13) and is reiterated here for clarity. The mixing screw had a lead length of 76.2 mm and a primary flight clearance of 0.08 mm. It had an 8-diameter long feed section that was 10.9 mm deep, a 6-diameter long transition section, and a 7-diameter long mixing section. The feed and transition sections were single-flighted, and the mixing section, shown in Figure 2, was designed with two channels. The channel depths were 3.18 mm at the entrance and exit of the mixing section, and within the mixing section they oscillated between 1.45 and 6.35 mm. The period of these oscillations was out of phase for the two channels. In addition, the flights between the channels were undercut to 1.40 mm deep at strategic locations so that flow could occur between the channels. The specific drag rate was calculated at 0.97 kg/(h rpm). The optical sensor was positioned over the top of the mixing section and it was observing both channels. The depth of the channels as viewed by the optical sensor is shown by Figure 3.

The confocal design of the sensor has been described previously (8) and is depicted in Figure 4. A sleeved sensor bolt was machined to receive an optical fiber that transmitted light from the light source. The lens, which is an essential feature of the design, focused the excitation light to a point in the resin. The resulting fluorescence was transmitted back through the lens to collection fibers that conducted the light to the detector. The collection fibers act as a pinhole and the point-to-pinhole confocal design is thus achieved. The focus position could be changed from the barrel wall to a maximum depth of up to 4 mm. The spatial resolution of the profiles reported here is 0.5 mm.

The fluorescence temperature method has been described previously (8,9). This technique involves measuring the fluorescence intensity at two wavelengths and calculating the temperature from a calibration function involving the ratio of the two intensities and the applied pressure. For perylene doped into polycarbonate resin, the two wavelengths of interest are 464 and 475 nm, and the calibration function for these measurements was as follows:

$$T = (807.3)\frac{I_{464}}{I_{475}} - 373 + 0.57\,P \qquad (1)$$

where T is the temperature in ^{o}C, I is the intensity, and P is the pressure in MPa. Equation (1) was obtained using a temperature-pressure calibration cell that was constructed with a standard 12.7 mm threaded port to accommodate the sensor. The pressure at the optical sensor was interpolated from the nearby pressure sensors in the barrel wall. The standard uncertainty in the temperature measurements was about 1.5 ^{o}C.

Temperature Measurements During Extrusion

The temperature measurement method was first used with the conventional screw with the 6 MFR resin. The extruder was operated at a screw speed of 20 rpm and data were collected from the optical sensor at an acquisition frequency of once every 0.5 s; i.e., 2 Hz or six temperature measurements per screw rotation. The sensor was focused at a position 0.95 mm from the barrel wall. The temperature measured is shown by Figure 5. As indicated by this figure, the temperature in the screw channel at 0.95 mm was about 278 ^{o}C. As the flight passed underneath the sensor, the focus point was below the surface of the flight, causing an increase in the temperature measurements. For these high temperatures, the fluorescence originated in the thin film of resin between the screw flight and the barrel wall and not from the desired focal point. These periodic high temperature measurements were between 282 and 288 ^{o}C. In order to calculate average temperatures for the position of focus, a filtering method was used to remove these high values, and only filtered data will be presented in the next sections. The discharge temperature from the extruder was measured at 287 ^{o}C using a hand-held thermocouple. This measurement is not subject to the heat transfer problems associated with normal process temperature measurements due to its isolation from heated metal parts. As will be shown later, this measurement was consistent with that measured by the optical sensor.

The temperature of the resin in the channel as a function of the channel depth was measured by moving the focus point away from the barrel wall, and the profile is shown by Figure 6. At a screw speed of 20 rpm and as previously discussed, the temperature was 278 °C at a distance of 0.95 mm from the barrel wall. The temperature was the lowest at a position about 2.0 to 2.5 mm from the barrel wall, and it increased at the barrel wall and at the root of the screw. The temperature gradient at the screw root indicated that an energy flux in through the screw was occurring. This energy flux in was caused by the temperature of the screw being higher than that of the PC resin near the root. The screw had a higher temperature at this location due to energy conducting from the hotter screw tip down the metal of the screw. The PC resin temperature near the barrel was about 279 °C, a temperature just slightly higher than the barrel temperature of 275 °C, indicating essentially zero energy transport through the barrel wall. Both of these energy fluxes are typical for this kind of process. The bulk temperature of the extrudate was measured for this case at 287 °C using a hand-held thermocouple. Calculation of the bulk temperature based on the data in Figure 6 would require knowledge of the velocity fields. Since the velocities are not known or calculated here, the bulk temperature can only be estimated by averaging the temperatures near the barrel wall where the downstream velocities are the highest. At the location of the sensor, the bulk temperature was likely about 279 °C, a temperature that is consistent with the downstream measured bulk temperature of 287 °C; i.e., as the material moves downstream viscous energy dissipation increases the bulk temperature of the resin.

The effect of screw speed on the temperature profile is shown by Figure 6 for the 6 MFR PC resin and the conventional screw. As expected and consistent with extrusion theory, the channel temperatures increased with increasing screw speed. Moreover, these data are consistent with the measured extrudate temperatures. The extrudate temperatures were measured at 287, 311, and 324 °C for screw speeds of 20, 60, and 100 rpm, respectively. Like the data at 20 rpm, the temperature was the lowest in the center of the channel, and the temperatures increased near the root of the screw and near the barrel wall. As expected the temperature of the resin near the screw root increased with increasing screw speed, consistent with the extrudate temperatures. The temperatures near the barrel wall at speeds of 60 and 100 rpm, however, are more difficult to explain. These temperature profiles indicate an energy flux from the barrel wall into the center of the channel; i.e. the barrel is in a heating mode. The barrel temperature, however, was maintained at 275 °C, a temperature less than the measured resin temperature near the wall of 287 °C, suggesting that the barrel is in a cooling mode. The reason for this discrepancy is unknown, but it may be related to the higher resin temperatures contributed from resin flow across the flight tip.

The effect of resin viscosity on the temperature profile at a screw speed of 60 rpm using the conventional screw is shown by Figure 7. As shown by this figure, the lower viscosity of the 23 MFR PC resin reduced the level of viscous dissipation in the screw channels and thus caused the temperature profile to be lower than that for the 6 MFR resin. These data are consistent with measured extrudate temperatures of 288 and 311 °C for the 23 and 6 MFR resins, respectively, and are consistent with extrusion theory.

The data presented above are for measurements at fixed depths away from the barrel wall and averaged over the angular direction. As previously discussed, the erroneous measurements that occurred when the focus point was in the metal of the screw were removed via filtering. Presently, the technique is not sensitive enough to provide measurements in the angular direction. Thus, a two-dimensional temperature space is currently not possible.

The temperature profile for the mixing screw was measured using the 6 MFR PC resin at 20 and 60 rpm, and the data are shown by Figure 8. Like the conventional screw, the channel temperatures increased in the mixing screw with increasing screw speed. Moreover, the mixing screw had temperature gradients near the screw surface that indicated an energy flux in through the screw root. The focus point of the probe at the deepest point, however, only approached the root of the screw for about 25% of the angular sweep due to the changing depth of the mixing section channel. Near the barrel wall, the temperatures were less than those for the conventional screw and the profile had a different shape. This result was likely due to the transport of cooler or solid material into the mixing channel. As the cooler material enters the mixer, some of it becomes trapped, melted, and mixed as it passes over the undercut flight (13). These thermal gradients were predicted previously using numerical methods (14), but this is the first time that they have been observed experimentally.

Discussion

The fluorescence analytical technique described here and elsewhere (8,9) was used to measure the temperature profiles in a rotating screw channel of a single-screw extruder. The data collected provided a very unique view of the temperature profiles that are unobtainable using other methods such as thermocouple probes and IR techniques. The perylene dye used provided a molecular probe, responding to the temperature environment at a local position.

Temperature data were measured for the metering section of a conventional screw as a function of the distance away from the barrel surface; i.e., into the channel of the screw. The data clearly showed that at the conditions used an energy flux in through the root of the screw was occurring. Moreover, these types of profiles are known to occur and have been predicted numerically (12). Temperature data that were measured as a function of screw speed and resin MFR were consistent with extrusion theory.

Currently, the method is not sensitive enough to provide a two-dimensional profile from the optical sensor; i.e., distance from the barrel wall and in the angular direction. Instead, the temperature is averaged over the width of the channel.

The method provided a very unique and never before observed view of the temperatures in a high-performance mixing screw. These data along with temperature profiles from the conventional screw indicate the transport of cooler or solid material into the mixing channel. As the cooler material enters the mixer, some of it becomes trapped, melted, and mixed as it passes over the undercut flights. All material entering the mixing section was forced across three 1.4 mm undercut sections prior to discharge. The optical sensor measured the temperature profile on the last of the three undercuts. The high shear and elongation fields in these undercuts are responsible for the improved mixing and melting capacity of the design (13).

Conclusions

The temperature profiles inside an operating single-screw extruder are extremely difficult to measure with accuracy using standard methods. These profiles, however, were measured here using a novel and non-invasive fluorescence analytical technique and perylene dye. The data provide new information for a high-performance mixing screw.

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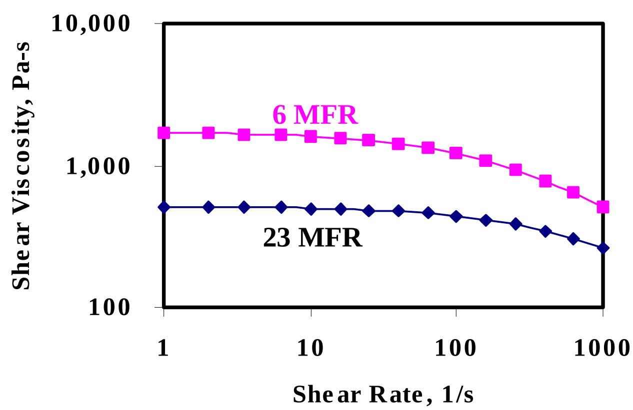

Figure 1. Shear viscosity of the PC resins at a temperature of 280 ^{o}C.

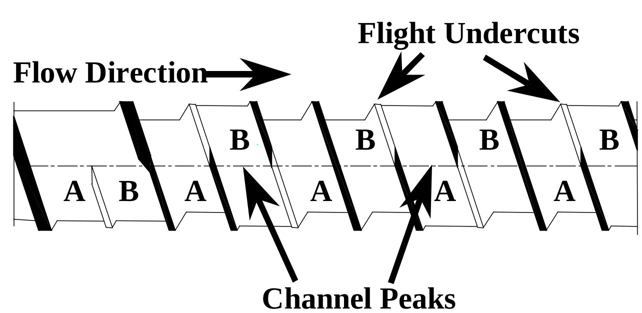

Figure 2. Schematic of the mixing section positioned in the metering section of the mixing screw (15).

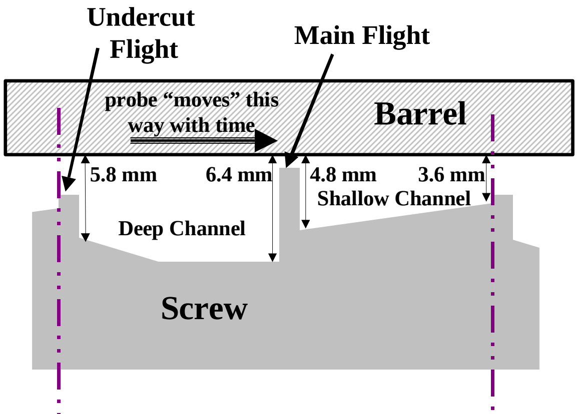

Figure 3. Channel depths for the mixing screw as viewed by the fluorescent optical sensor. The sensor is located 19 diameters from the start of the screw.

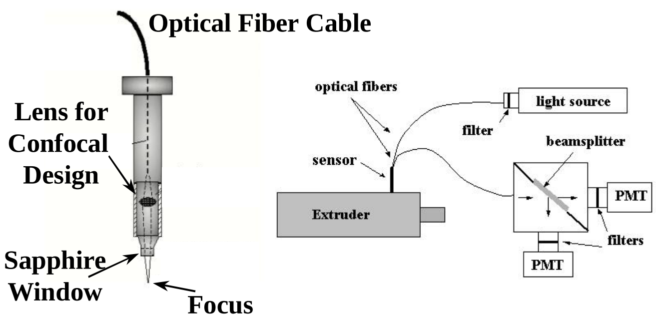

Figure 4. Schematic of the optical sensor and the measurement equipment attached to the extruder; the PMT is a photomultiplier tube.

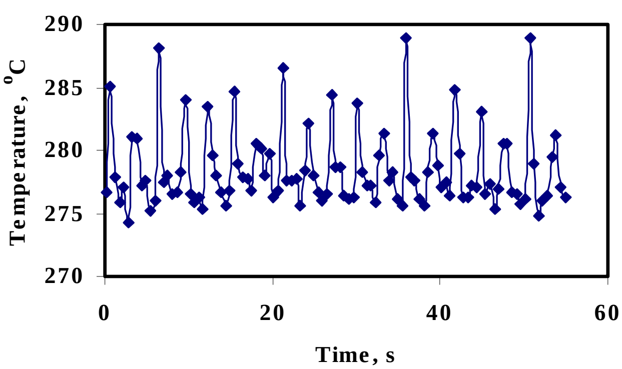

Figure 5. Temperature data for the conventional screw at a screw speed of 20 rpm using the 6 MFR PC resin. The optical sensor was positioned 0.95 mm from the barrel wall.

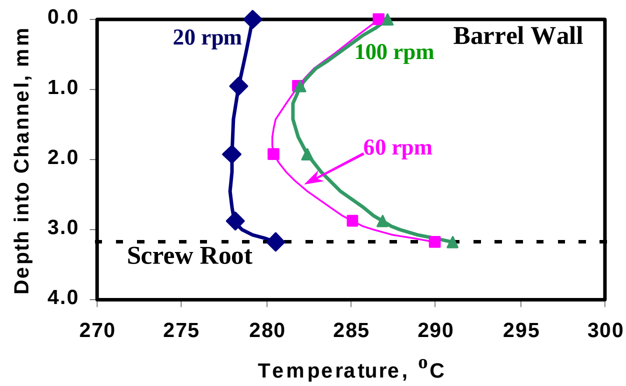

Figure 6. Temperature profile for the conventional screw and the 6 MFR PC resin as a function of screw speed.

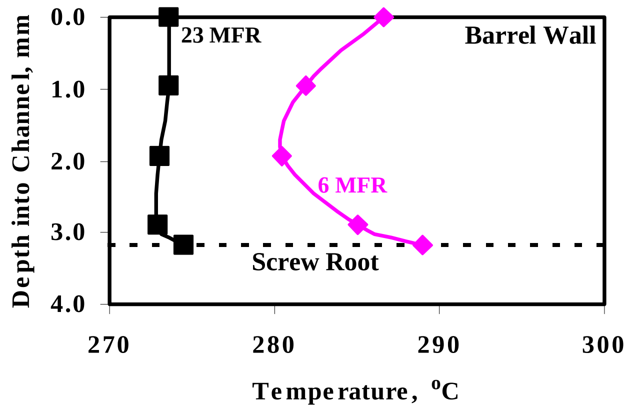

Figure 7. Temperature profile for the conventional screw at 60 rpm using the 6 and 23 MFR PC resins.

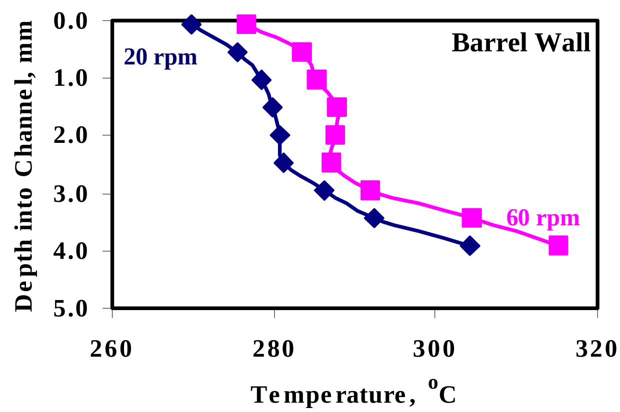

Figure 8. Temperature profiles for the mixing screw using the 6 MFR PC resin.

Key Words: Temperature Measurement, Fluorescence, Single-Screw Extrusion, PC, and Polycarbonate.